Matching of Electronic Generators with Piezoelectric Vibrating Systems for Increase in Efficiency of Ultrasonic Devices

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***Abstract* – The paper is devoted to methods of the matching of ultrasonic vibratory systems with electronic oscillators, for automatic maintenance of optimum behaviour of energy transfer from the electronic oscillator to ultrasonic vibratory system. The results confirming the efficiency of the proposed method were presented.**

***Index Terms* – Matching, piezoelectric transducer, ultrasonic oscillator.**

I. INTRODUCTION

FOR ULTRASONIC processing of technological media and materials specialized and multi-purpose technological devices are used, which provide conversion of electric energy into ultrasonic vibrations and their introduction in the processed medium. Independently of their function ultrasonic technological devices consist of the electronic generator and the ultrasonic vibrating system. The electronic generator performs conversion of energy of alternating-current from current networks into electric vibrations of ultrasonic frequency for power supply of the ultrasonic vibrating system. The ultrasonic vibrating system realizes the conversion of electric vibrations into mechanical ones of the working surface and their entering in processed medium or material.

II. THEORY

For realization of conversion in the ultrasonic technological devices piezoelectric and magnetostriction transducers are used.

At present due to the simplicity of production and increased efficiency the ultrasonic vibrating systems with piezoelectric transducers are widely applied.

The piezoelectric vibrating system is generally a complex electric load on the electronic generator and its connection to it does not provide maximum efficiency of energy transfer.

For detection of reasons for non-optimal matching of the piezoelectric transducer and the electronic generator consider the physical (electrical) equivalent circuit of the vibrating system presented in Fig. 1 with the piezoelectric transducer operating in nonresonant mode [1].

In the presented circuit inductance Lm is equivalent to fluctuating mass of the system, capacity Cm is a flexibility, active resistance Rp is mechanical loss resistance, Rs is a radiation resistance of the vibrating system, C is a static capacity of the transducer, Rd is dielectric loss in piezomaterial.

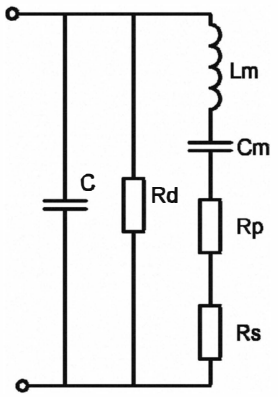

Fig. 1. Equivalent circuit of piezoelectric vibrating system near resonant frequency

Mechanical loss resistance is caused by internal friction of the material particles at vibrations, as well as by mechanical power loss in the places of fastening of the vibrating system. Radiation resistance is determined by parameters of the radiator and is proportionate to wave resistance of the medium. Capacity of the piezoelectric transducer depends on geometric sizes and permittivity of used piezoceramic elements.

On resonant frequency of the mechanical vibrational contour (Lm, Cm) electric equivalent circuit of the piezoelectric vibrating system is transformed to the view shown in Fig. 2.

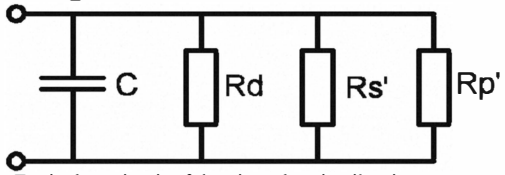

Fig. 2. Equivalent circuit of the piezoelectric vibrating system on resonant frequency

Here Rs' and Rp' are resistances resulted in parallel circuit [1]. As it is clear from the equivalent circuit of the piezoelectric vibrating system it is a complex loading for the electronic generator determined mainly by capacity of the piezoelectric transducer. Direct connection of such load to the electronic generator leads to decrease in effectiveness of power transfer in load and, consequently, to the decrease in efficiency of ultrasonic influence on

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processed media and materials. To provide maximum efficiency of conversion and transfer of acoustic energy into processed media there is a need to ensure coordination of the electronic generator and the ultrasonic vibrating system.

In the general case input impedance of the ultrasonic vibrating system and output impedance of the electronic generator are complex values (1).

$$\begin{cases} Z_{UOS} = a_{UOS} + b_{UOS} j \\ Z_G = a_G + b_G j \end{cases} \quad (1),$$

where:

Z_{UOS} is impedance of the piezoelectric vibrating system;

a_{UOS} is active component of impedance of the piezoelectric vibrating system;

b_{UOS} is reactive component of impedance of the piezoelectric vibrating system;

Z_G is output impedance of the generator;

a_G is active component of impedance of the generator;

B_G is reactive component of impedance of the generator.

The active impedance component of the piezoelectric vibrating system is determined by construction diagram (geometric sizes) of the ultrasonic vibrating system, as well as by medium, in which ultrasonic vibrations are introduced. The reactive impedance component of the ultrasonic vibrating system is determined by sizes and properties of system material (it is shown during operation of the ultrasonic vibrating system at nonresonant frequency), as well as by medium, in which ultrasonic vibrations are introduced. Moreover, the reactive component includes a capacitive component determined by dielectric properties of piezoceramic material.

Thus, for matching it is necessary to operate on the resonant frequency of the ultrasonic vibrating system; output active resistance of the generator should be minimal to decrease dissipation of active power (coordination in voltage), and the reactive capacitive component of the system should be compensated by reactive inductive components of output stage of the generator.

$$\begin{cases} a_G << a_{UOS} \\ |b_G| = |b_{UOS}| \\ f = f_{\text{resonance}} \end{cases} \quad (2)$$

As mentioned above, the vibrating system operating on its resonant frequency is an electric active capacitive load for the electronic generator. Output resistance of the electronic generator is, as a rule, merely active resistance. That is why, for compensation of static capacitance of the piezoelectric transducer the method presented in Fig. 3 is used. The reactor is sequentially switched on with the piezoelectric transducer of the vibrating system [2]. Reactor inductance is chosen in such a way that resonance of electric sequential vibrational contour generated by throttle inductance and capacity of the piezoelectric transducer is several kilohertz (4–5) higher than frequency of mechanical resonance (resonant frequency of the vibrating system). Limited matching of frequency of electric contour and frequency of mechanical vibrations is performed to reduce influence of capacity changes of piezoelectric elements of the transducer [5]. Matching of active resistance component of output stage of the generator and input resistance of the system (on resonant frequency) is achieved with help of output transformer of the generator.

Such method of capacity compensation allows approximating the mode of electric load connected to the generator to the active one (during operation on resonant frequency of the ultrasonic vibrating system).

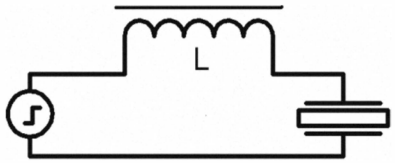


Fig. 3. Compensation of static capacitance of the piezoelectric vibrating system

The examined matching method has essential disadvantages reducing efficiency of matching between the generator and the vibrating system. Impossibility of optimal matching is reasoned by the fact that at temperature changes of the system during the operation capacity of the piezoelectric elements changes which results in changes of matching conditions.

Moreover, changes in medium parameters taking place during the processing (concentration of dissolved substances, emulsification, dispersion, swelling leading to change of viscosity, acoustic impedance, temperature, pressure, etc.) change parameters of the vibrating system that lead to changes in coordination conditions.

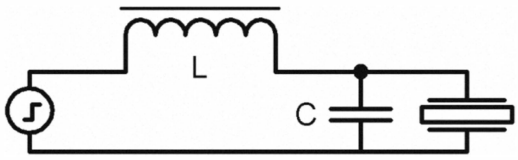


Fig. 4. Method for minimization of changes of static capacitance of the piezoelectric vibrating system

For partial solving of the considered problem most developers [5] of ultrasonic equipment recommend to minimize changes of capacity of the piezoelectric transducer due to application of additional capacity connected parallel to piezoelectric elements (Fig. 4.) Such approach allows reducing influence of changeable capacity of the transducer on the position of resonance of the electric vibrational contour; however this method cannot provide compensation of influence of changes in medium parameters on the parameters of the vibrating system.

III. ADAPTIVE MATCHING

It is evident that to provide continuous coordination of the ultrasonic vibrating system with the electronic generator at all possible changes of system and medium parameters it is necessary to change inductance of compensating reactor.

The further several variants of realization of this matching method are considered.

The most easily realizable method for stepped parameter tuning of matching inductor made in the form of separate, series connected sections is demonstrated in Fig. 5. At its realization change in inductance is provided through disconnection of necessary numbers of inductors.

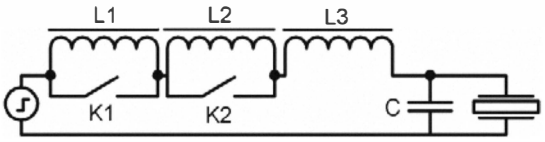


Fig. 5. Method for step control of inductance of matching inductor

Such method of inductance control is not optimal, as it does not allow realizing smooth adjustment during the operation.

The second of possible variants of such matching (put in practice in case of application of several vibrating systems in ultrasonic devices) is presented in Fig. 6.

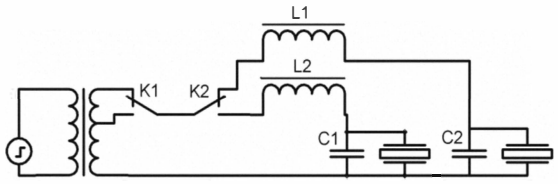


Fig. 6. Matching contour for connection of two vibrating system

In this case each vibrating system is connected to its matching unit. Switching of vibrating systems is realized by contacts of relay K2. Relay K1 allows changing supply voltage of the vibrating system, if necessary. This method is used, when it is necessary to connect two vibrating systems with essentially differing parameters to the electronic generator.

Fig. 7 presents the variant of matching unit with convertible inductor, which allows smoothly changing inductance of matching inductor during the operation.

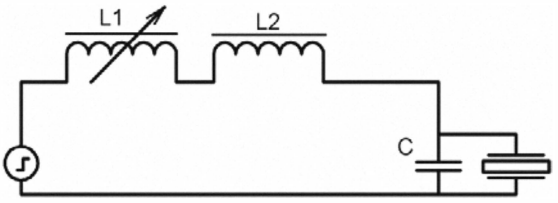
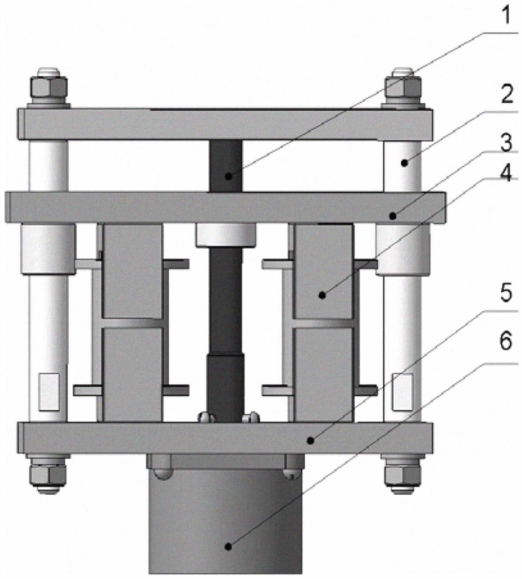


Fig. 7. Matching contour with convertible inductor

The inductor with convertible air clearance [3] directed by step motor with the help of screw-gear can be applied as a convertible inductor (Fig. 8). In the construction (Fig. 8) two inductor (switching on in series or in parallel) controlled by one step motor are used. Metal plate, on which moving parts of cores are fastened, travels on the iron guide rails, which prevents skewness and allows achieving even changes of magnet gap within the whole range of tuning. The use of step motor ensures the control of reactor inductance by changing of magnet gap during the operation, as well as setting minimum clearance in the core preventing saturation of the magnetic circuit. Due to strict dependence of rotation angle of engine shaft, there is no need to use position sensors of mobile cores.

As change in inductance value of the reactor from the value clearance is nonlinear, use of step motor gives an opportunity to control clearance in the core, as well as to linearize rate of change of reactor inductance by means of rate control of change of clearance.



1 – moving screw, 2 – guide rail, 3- moving plate, 4 – moving ferrite core, 5 – fixed plate (base), 6 – step motor.
Fig. 8. Inductor with adjusting clearance

The use of reactor inductance with adjusting clearance in the core is not practical in compact and low-power devices because of their short operation speed, large overall size and relatively high power consumption.

That is why to provide tuning of reactor inductance at the designing of low-power ultrasonic devices (up to 1000 VA) the most effective method is to use saturable reactors, in which inductance depends on the current in bias winding. The operation of such reactor is based on dependence of value of magnetic inductivity on the value of magnetic field

$$\mu = f(H) \qquad [4].$$

Fig. 9 presents the scheme of saturable reactor with series connection of operating windings.

As it is shown, the inductor consists of two inductors, power windings of which are connected sequentially, and bias windings are connected coming from the opposite directions, which, in the case of identity of inductor windings, allows ridding of ac component in the bias circuit.

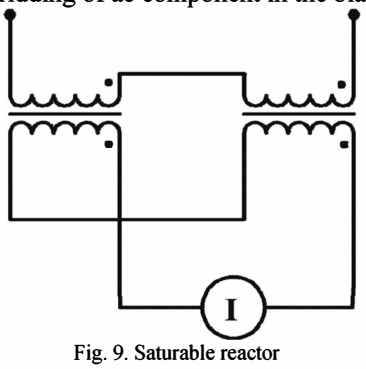


Fig. 9. Saturable reactor

To manage the process of reactor tuning it is necessary to obtain information on the value of reactive component

of impedance of the vibrating system, which should be compensated. For realization of method for continuous control and compensation process control special controlling unit has been developed, the block diagram of which is shown in Fig. 10.

Fig. 11. Basic electric circuit of control unit

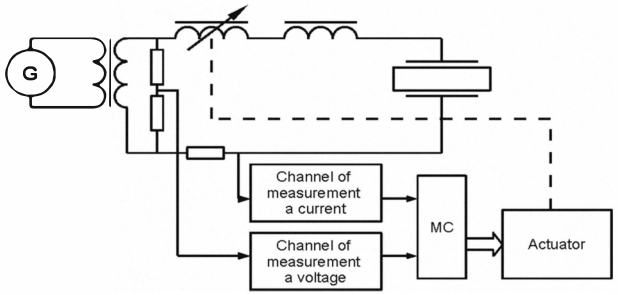


Fig. 10. Block diagram of control unit

The basic electric circuit of the control unit intended for work with the inductor with variable clearance is presented in Fig. 11.

The control unit consists of two comparators for channel of voltage and channel of current of directive microcontroller and driver of the step motor. Fig. 12 demonstrates one of the possible operating algorithms of directive microcontroller.

During initialization of the operating mechanism consistent convergence of the cores of the inductor and setting of initial clearance in the cores of the reactor take place. Then, after authorization of operation of matching system the correction cycle of the inductance of controlled inductor (changes of core clearance) begins; for this purpose consistent measurement of phase shift between current in the circuit of the ultrasonic vibrating system and voltage on the input of matching unit occurs. On the base of the results of continuous control the decision on the direction and rate of change of inductance is made. Further the cycle is repeated until prohibition of matching system operation or at reaching of change limit of inductance. In last case the error signal is given.

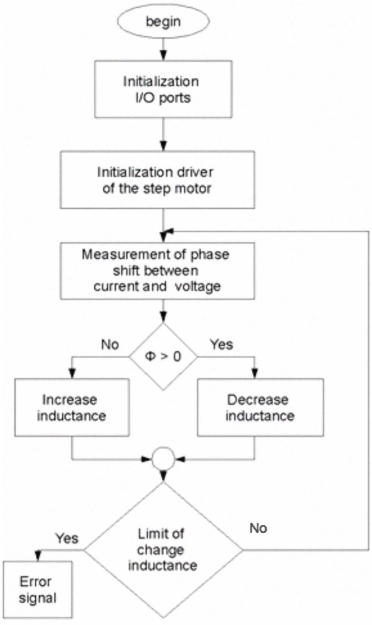


Fig. 12. Block diagram of operating algorithm of the control unit

IV. RESULTS

For the experimental check of matching efficiency number of studies aimed at measuring of acoustic power entered into liquid medium (water) at fixed tuning of

matching contour and at use of the correction system of the matching contour during the operation was carried out. The results are shown in Fig. 13.

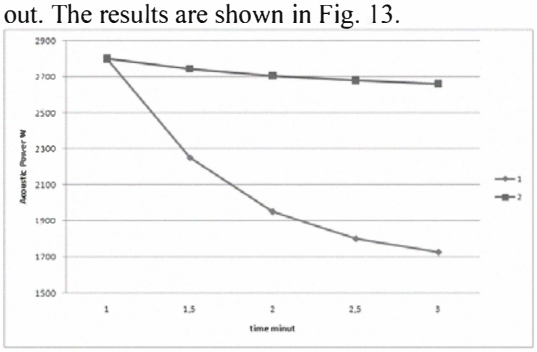


Fig. 13. Changes of acoustic power during the technological process at fixed tuning of matching contour (1) and at application of matching convertible contour (2)

As it follows from the presented dependences the entered acoustic power at fixed tuning of matching contour rather quickly decreases, it is closely related with mismatch due to changes in temperature of the piezoelectric transducer of the ultrasonic vibrating system and changes in properties of processed media. At the same time at correction of the matching contour acoustic power entered into processed media decreases insignificantly. In total, efficiency of the device with adjusted reactor increases in 10-15% in comparison with the ultrasonic devices, in which reactor of matching contour is set to mean value.

In Fig. 14 and Fig. 15 photographs of the control unit and the inductor are presented.

Fig. 14. Control unit

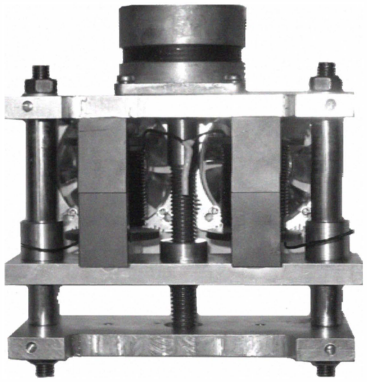


Fig. 15. Controlled inductor with convertible clearance

Fig. 16 presents the photographs of the low-power electronic generator with matching system on the basis of saturable inductor.

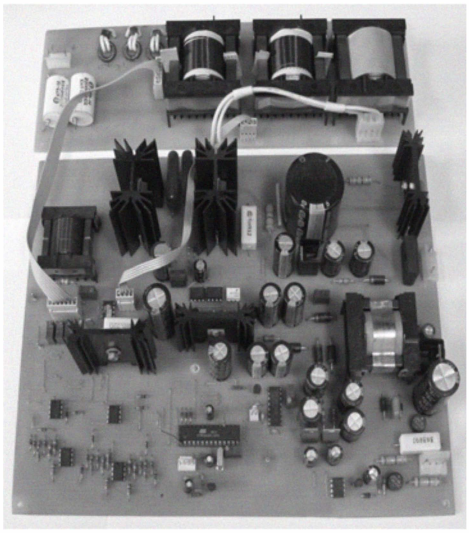


Fig. 16 Ultrasonic generator with matching system

V. CONCLUSION

Development of optimal system for matching of output resistance of the electronic generator and input resistance of the piezoelectric vibrating system based on realization of continuous control of input electric parameters of the vibrating system and continuous change in inductance of compensating inductor provides increase in efficiency of ultrasonic exposure at the application of ultrasonic technological devices with power up to 8 kVA with realization of different technological processes due to:

1. Providing an optimal mode of generator output stage by means of continuous reduction of load impedance to active value at changeable modes;
2. Providing optimal modes of ultrasonic energy entering at any changes in processed medium (viscosity, pressure, temperature);
3. Increase in electroacoustical efficiency of ultrasonic technological devices in 10-15%.

REFERENCES

[1] Donskoy A.V. Ultrasonic electrotechnological settings. Leningrad: Energoizdat, 1982 208 p. il. in Russian

[2] Zernov N.V., Karpov V. G. Theory of radio engineering circuits/ – Leningrad: Energy, 1972 – 816 p. in Russian

[3] Vladimir N. Khmelev, Senior Member, IEEE, Roman V. Barsukov, Dmitry V. Genne, Student Member, IEEE "The self-action agreement system of electronic generator with the piezoelectric oscillatory system" Intrnational Workshops and Tutorials on Electron Devices and Materials EDM'2007: Workshop Proceedings. - Novosibirsk: NSTU, 2007.

[4] Livov E. L. Magnetic amplifiers in technique of automatic control. Moscow, «Energy», 1972. 552 p. il. in Russian

[5] Khmelev V.N., Leonov G.V., Barsukov R.V., Tsyganok S.N., Shalunov A.V. Ultrasonic Multifunctional and Specialized Equipment for Intensification of Technological Processes in Industry. Barnaul: AltGTU, 2007. – 414 p. in Russian

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